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Comparative Study of Thermal Insulation Alternatives for Buildings, Walls and Roofs in Makkah, Saudi Arabia.

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دراسة مقارنة لعدة بدائل للعزل الحراري في وحدات جدران وأسطح المباني بمكة المكرمة

تمثل الجدران والأسقف الغلاف الخارجي للمباني، والذي يقوم بحمايتها من العوامل المناخية الخارجية، ويساعد على تحقيق الراحة الحرارية بالحيزات الداخلية فقط إذا تم تصميمه وفقاً لمعايير ومواصفات خاصة ينبغي دراستها وتعيينها بدقة. وتختص هذه الدراسة بمقارنة الأداء الحراري لوحدات من جدران وأسقف مختلفة، تستخدم في تشييد المباني بمكة المكرمة في المملكة العربية السعودية، حيث تهدف إلى الوصول بالتصميم المتكامل لتلك الوحدات إلى الحلول المثلى من حيث تحقيق الأداء الحراري المتوازن. وفي محاولة لبلوغ تلك الأهداف، يتم حساب الكسب والفقد الحراري وتحليله عبر طبقات مركبة لنماذج عددية تضم خمساً من تركيبات الجدران واثنتين من تركيبات الأسقف على أن يحوي كل منها العزل الحراري اللازم، مع الأخذ في الاعتبار التأثيرات المختلفة لدرجات الحرارة الخارجية، ونسب الحجوم والمساحات للحيزات المعرضة للإشعاع الشمسي بموقع الدراسة، وكذا وضعية الطبقات المختلفة للحوائط والأسقف وترتيبها. ومن خلال مقارنة النتائج للحلول التحليلية المختلفة، ثم إجراء التعديلات، وإعادة ترتيب النماذج الحسابية، أمكن الحصول على أفضل الحلول المدمجة للبدائل المقترحة للمواد المستخدمة في بناء الجدران والأسقف من حيث الأداء الحراري تحت الظروف والشروط المناخية لمدينة مكة المكرمة، الأمر الذي يؤدي إلى تحقيق الوفر في الطاقة المستهلكة بالمباني إلى جانب توفير الراحة الحرارية لمستخدميها.

Abstract

The use of thermal insulation in buildings has increased significantly in recent years and has become mandatory in some countries. This was due to higher demands on human thermal comfort inside residential, commercial, and governmental buildings, beside the ever increasing costs of energy production and its negative impact on the environment. This paper is concerned with the role that insulation can play in wall and roof configurations to sustain better thermal conditions indoors. It aims to approach the optimum design criteria of thermal insulation for wall and roof configurations of the prototype building in Makkah, Saudi Arabia. To attain the goal of the study, a numeral application on five-wall configurations and rather two-roof was developed and analyzed with a feedback process to identify optimum solutions.

Experiments of various building forms, ratios, and integration of wall and roof components were tackled, whilst thermal performance measures for each case were calculated. The conclusion of this paper embodies the importance of developing proper layer arrangement and configurations for walls and roofs as they have major influence on energy efficiency of the interiors. Reduced energy consumption of the building and increased human thermal comfort are, therefore, anticipated as sustainable design features to be achieved.

Keywords: thermal insulation, building walls, building roofs, heat transfer.

INTRODUCTION

Wall and roof shape the key solution for occupants to extreme weather conditions occurring outside. The design of these elements is crucial since they assist the designers and engineers to achieve occupants comfort within buildings. In hot climate, designers should consider climatic factors that influence building form, orientation, design and construction. This necessitates the designer to understand those climatic factors considerably. In addition, designers should understand the integrated performance of overall building components in order to promote the ability to predict architectural design performance in advance.

Among the many factors to be considered, thermal loads of buildings depend on the indoor design temperature, the outdoor prevailing climatic conditions, and the choice of building construction materials and insulations (Al-Sanea, 2000). It should be emphasized that when determining the most economical wall and slab configurations implying the insulation selection for each and the optimum thickness with respect to some certain application, other material properties should be considered such as water absorptivity, strength, ignition temperature, and smoke release. It had been emphasized that the cost of insulation materials, cost of electricity, etc., can vary substantially with time and region and that would affect the optimum thickness (Al-Sanea *et al*, 2003). Hence, proper design and use of insulations in building structures necessitates a thorough assessment of the detailed thermal characteristics of the structure under various influential parameters.

AIMS

Based on an intensive analysis of choosing layer material for both walls and roofs, this paper focuses on the design of wall and roof that in turn will help find out the proper materials for the prototype building in Makkah, Saudi Arabia. With a thorough application of different materials, the main goal of the study is to achieve better thermal performance of wall and roof elements in Makkah. Additionally, the study focuses on the main factors to be considered through the design and analysis processes, including building shape and area, U values, air volumes, and temperature differentials.

METHODOLOGY

In order to understand the integration of overall building performance, the study examines the potential impact of different material selection on the thermal performance of walls and roofs. In a further step, the feedback and modification would change the design through different analysis stages. The design analysis will be based on:

a. experiments of building components and their integration with analysis procedures;
b. calculations of building's thermal performance (heat loss and heat gain); and
c. modifying the prototype design with thermal analysis progress.

ANTICIPATED RESULTS

The anticipated results of the study are to determine proper material selections for a prototype building in Makkah and identify the optimum building shape.

PREVIOUS STUDIES

A wealth of information and data with respect to thermal properties and analyses are offered in previous studies and presented in various literature. Relevant conclusions were arrived at by Al-Nafeez et al. who assessed insulation materials on the basis of time lag, decrement factor, cost, and R-value (Al-Nafeez et al.,1990). Zaki et al. predicted thermal performance of a two-layer composite wall with periodic change of the outside air temperature and solar insolation (Zaki et al.,1986). Eben Saleh evaluated the performance of different arrangements and thicknesses of building insulation within the outer side of the building envelope (Eben Saleh ,1990-1, 1990-2). Eben Saleh had later examined adobe as a building material and proved that it is a thermal regulating and not a conducing material (Eben Saleh ,1990-3).

By Fourier transforming the heat conduction equation to the frequency domain, Lindfors et al., had formulated a technique for estimating thermal properties of building components from in situ measurements (Lindfors et al., 1995). Later, a so-called state-space model was derived by Norlen for estimating the thermal properties that were assumed to be constant. However, this model could be applied only to a single homogeneous slab with negligible radiative and convective fluxes (Norlen, 1995). Keeping constant the overall thickness and thermal transmittance of a three-layered building envelope, Bojic et al. investigated the influence of layer distribution and thickness on thermal behavior (Bojic et al.,1997).

Using a whole building dynamic modeling performed in a continuously utilized house, Kossecka et al. proved that walls with massive internal layers have better annual thermal performance than those with inside insulation (Kossecka et al.

1998). Al-Sanea et al. had also shown that the wall orientation has a significant effect on the heat transfer characteristics, but a relatively smaller effect on the total cost and optimum thickness for a given insulation material. In the same literature, they referred to the total cost and optimum insulation thickness and their sensitivity to changes in the economic parameters (Al-Sanea et al.,2002).

Using a finite volume implicit method, the effect of the location of the insulation layer in building walls on the initial transient heat-transfer response was investigated by Al-Sanea et al. (Al-Sanea ea al., 2001-1). They studied the effect of insulation location on the thermal performance of building walls under steady periodic conditions. Using the climatic data of Riyadh, the results showed that the insulation layer location had a minimal effect on the daily mean heat transmission load, with a slight advantage for the outside insulation in summer and the inside insulation in winter. The outside insulation gave smaller amplitude of load fluctuation and smaller peak loads in both summer and winter for all wall orientations (Al-Sanea ea al .,2001-2).

Throughout this preview, it could be noted that an extensive research work has been recorded into the influence of wall and roof design and insulation to energy behavior. However, the corresponding performance and influences of other factors such as building shape and area, U-values, air volumes, and temperature differentials are not much considered in any of these studies. Correspondingly, an optimized overall thermal design of buildings to promote a *combined* design performance prediction is the issue to be particularly stressed in this study.

BUILDING SHAPE

There are three main variables which affect the rate of heat loss or gain from a building: 1) total area and U value; 2) the volume of air in the building; and 3) temperature difference (Ashrae,1989). Recognizing those variables will help the designer to understand the influence of the overall building component with respect to construction form. A designer of a building can simply affect the first variable by making changes in the choice of materials and the form of construction. These changes can significantly affect both the U-value and the method of construction. However, a designer is able to manipulate and emphasize those variables altogether. For any enclosed volume, there are many ways in which dimension of height, length and width can vary. resulting in different total surface area without changing the volume of the enclosure. Thus, in case of two buildings, both having the same volume and built of the same material, quite different surface area may be encountered, and hence, different rates of fabric heat loss will develop (Ashrae,1989).

RELATIONSHIP BETWEEN SURFACE AREA AND VOLUME

The relationship between surface area ratio and volume is an important factor to be considered. This relationship is based on the height, length, and width proportions and ratios. As illustrated in Figure 1, it can be noticed that surface area differs as the enclosure dimensions vary within the same volume. In each case the volume was kept constant, while the surface area was altered, thus giving different values for the surface area-to-volume ratio.

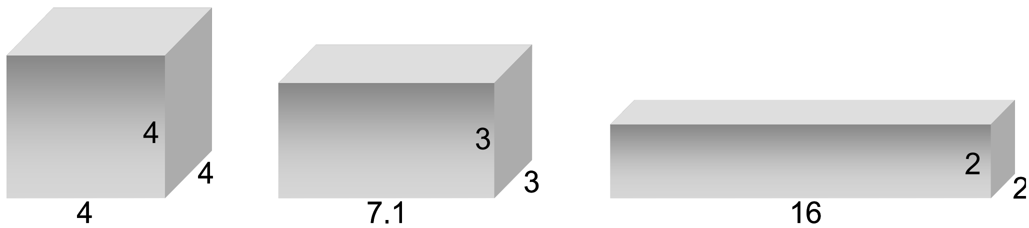


Figure 1. Variations of surface areas with the constant volume.

ANALYSIS OF WALLS AND ROOFS

Walls and roofs are the envelop of buildings. Moreover, they form an integration and relationship between indoor and outdoor spaces. In this section, an intensive thermal analysis of wall and roof will be made to help determine the best wall and roof combination. This selection is influenced by the temperature variations in Makkah throughout the year. Five different wall selections are designed to find out the best wall selection in terms of thermal resistance. Since Makkah lies in a hot-dry climatic region, the R, U, and q-values, and calculation methods should be based on the *heat gain* scenarios. The basic dimension of building height, length, and width are shown in Figure 2.

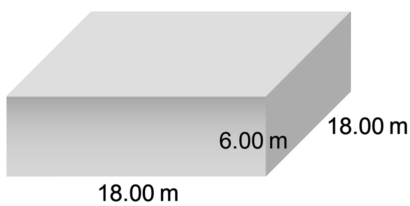


Figure 2. The basic dimension of building height, length and width.

In addition, the maximum monthly temperature of Makkah will be used for calculating The R, U and Q values, Figure 3. These monthly temperature readings were taken in 1989 (University service library, 1992). Thermal Resistance "R-value" of different wall materials is shown in Table 1 (Ashraea Fundamentals, 1989).

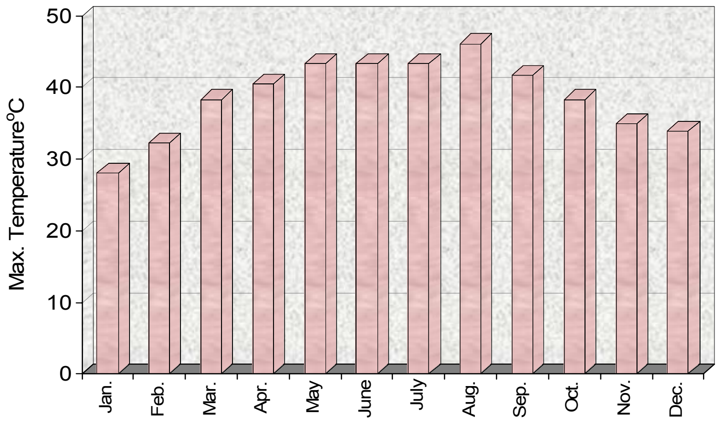


Figure 3. Monthly maximum temperatures of Makkah in 1989.

Table 1. Wall materials with their thermal resistance values and thicknesses.

Material	Thickness (mm)	R-value (m^2 K/W)
Gypsum board	12.50	0.008
insulation material	75.00	2.78
water proof	Neglected	neglected
air space	37.50	0.43
face brick	100.00	0.56

WALL ALTERNATIVES

The first wall alternative is detailed in Figure 4 and the following equations as the prototype. Additional four wall configurations are, then, selected to substitute the first alternative as compared in Table 2. The reason for choosing these alternatives is to determine the optimum wall configuration that would perform the best in terms of thermal efficiency.

Total R-value = 0.008+ 2.78+ 0.008+ 0.43+ 0.56 = 3.786 m^2 K/W

h_i "convection coefficient inside" (non reflective) = 8.29 W/m^2 K

h_o "convection coefficient outside" (for summer time) = 22.71 W/m^2 K

$$U = \frac{1}{1/h_i + TotalR + 1/h_o} \quad (1)$$

$$U = \frac{1}{1/8.29 + 3.786 + 1/22.71} = 0.25 \text{ W/m}^2 \text{ K}$$

Outside and inside temp.(t_o& t_i) = 41 & 24 °C

Total area of one wall (A) = 100.00 m^2

Q-value = U 3 A_{wall} 3 (t_i- t_o) (2)

Q = 0.25 3 108.00 3 (24-41) = 459 W

Q-value total for four walls = 45934 = 1836 W

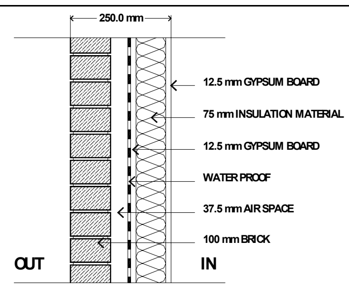


Figure 4. Detailed section of prototype wall (first alternative).

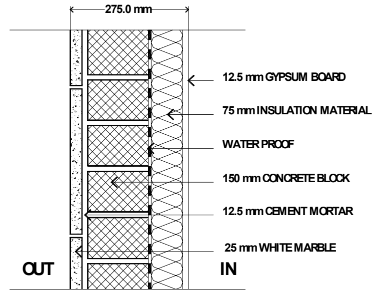
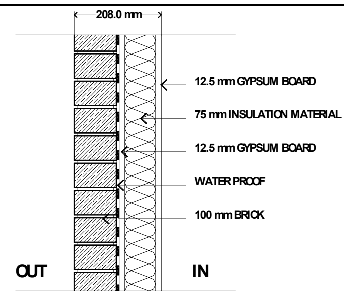
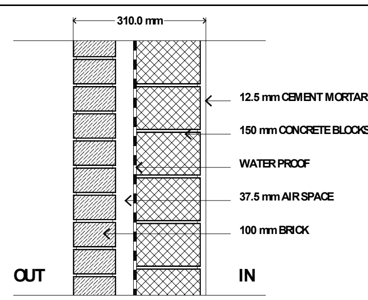
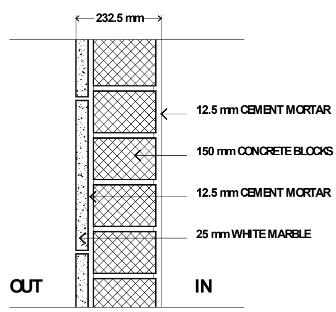
Wall type	U & Q-value calculations	Detailed section of alternatives
Second alternative	Total R = 3.53 m^2 K/W $U = \frac{1}{1/8.29 + 3.53 + 1/22.71} =$ 0.27 W/m^2 K Q-value (for four walls) = 0.27310831734 = 1983 W	
Third alternative	Total R = 3.50 m^2 K/W $U = \frac{1}{1/8.29 + 3.50 + 1/22.71} =$ 0.27 W/m^2 K Q-value (for four walls) = 0.27310831734 = 1983 W	
Fourth alternative	Total R = 1.66 m^2 K/W $U = \frac{1}{1/8.29 + 1.66 + 1/22.71} =$ 0.55 W/m^2 K Q-value (for four walls) = 0.55310831734 = 4039 W	
Fifth alternative	Total R = 0.70 m^2 K/W $U = \frac{1}{1/8.29 + 0.70 + 1/22.71} =$ 1.16 W/m^2 K Q-value (for four walls) = 1.16310831734 = 8519 W	

Table 2. Calculations and detailed sections of wall alternative configurations

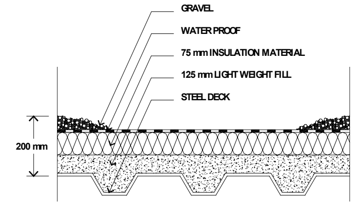
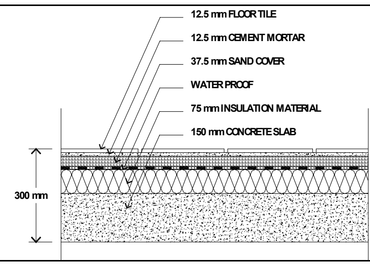
Roof type	U & Q-values calculations	Detailed section of alternatives
First alternative	R = 3.03 m^2 K/W $U = \dfrac{1}{1/8.29 + 3.03 + 1/22.71}$ = 0.313 W/m^2 K Q-value for roof = 0.313 3325317 = 1729 W	
Second alternative	R = 3.07 m^2 K/W $U = \dfrac{1}{1/8.29 + 3.07 + 1/22.71}$ =0.309 W/m^2 K Q-value for roof = 0.309 3325317 = 1707 W	

Table 3. Calculations and detailed sections of roof alternative configurations

TOTAL U-	WALL TYPE	ROOF TYPE	JANUARY	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEP	OCT	NOV	DEC
0.56	1	2	3069	4059	3933	4059	4455	4257	4653	4059	4455	3465	3069	3465
0.58	2	1	3020	3875	3542	3875	4253	4364	4442	3875	4253	3308	3020	3308
0.58	3	1	3020	3875	3542	3875	4253	4364	4442	3875	4253	3308	3020	3308
0.86	4	2	5301	7011	6669	7011	7695	7353	8039	7011	7695	5877	5301	5877
1.47	5	1	10072	13321	12671	13321	14621	13971	15270	13321	14621	11672	10072	11672

Table 4. The total U-values (W/m^2 K) and Q-values (W) of each wall and roof combination.

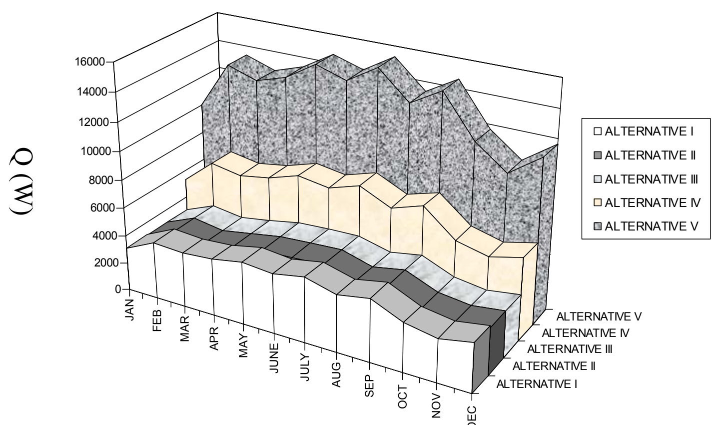


Figure 5. Comparison performance chart of the five alternatives.

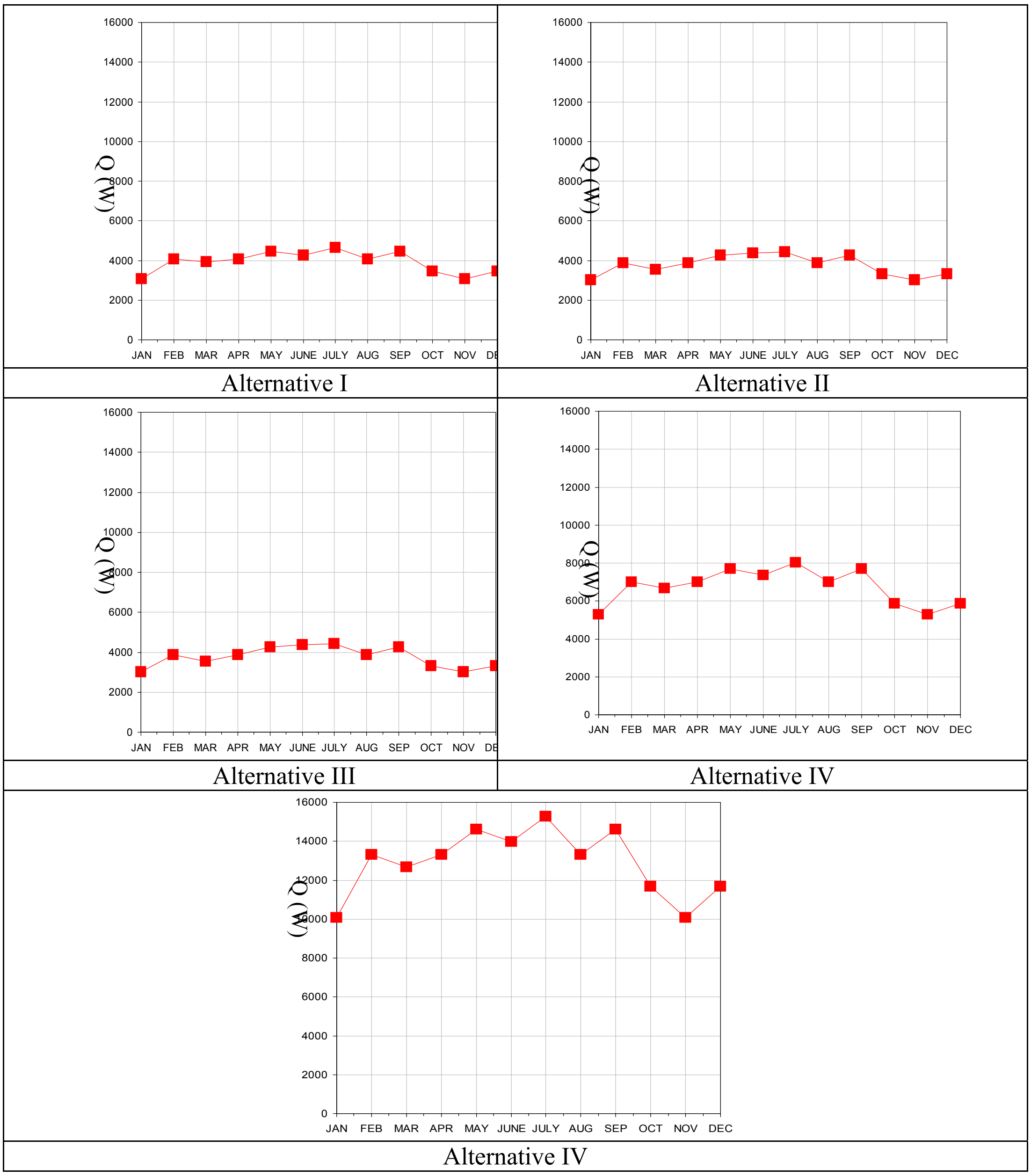


Figure 6. The performance of the five alternatives over the year.

ROOF DESIGN AND ANALYSIS

Two roof configurations are examined to find out about the most suitable roof in terms of thermal insulation, Table 3.

Table 4 and Figure 5-6 show the Q-values for each of wall and roof selection. These values are different from one month to another because of the monthly temperature differences.

FINDINGS AND RESULTS

The results achieved from wall and roof design combinations to form the building enclosure can be discussed as the following:

- The combination of wall 2 and roof 1 (second choice in the table) is the most optimum selection in terms of thermal performance for Makkah during summer months.
- Despite that, the second combination of the wall alternative differs from the third one, U-value and Q-value for both of them are the same.
- From the charts, it can be obviously recognized that thermal performance can increase depending upon the wall and roof combination selection.
- The fifth alternative demonstrates the weakest performance in terms of thermal efficiency.
- Though their wall thicknesses are different, the second and third selections resulted in the same thermal performance (same U-value and Q-value).
- Winter time is from November to February.
- Assuming winter time to occur from November through February, the combination of wall 5 and roof 1 are the most optimum integrated configuration in terms of thermal resistance during winter period (heat loss).

THE THERMAL CUBE ENCLOSURE

ROOF SHAPE

A change of wall height and roof areas with a constant volume will have different resultant of total heat transmission as well as thermal efficiency of both wall and roof. Various plan shapes will be examined at this stage with the same material components and configurations of walls and roofs discussed above, Figure 7.

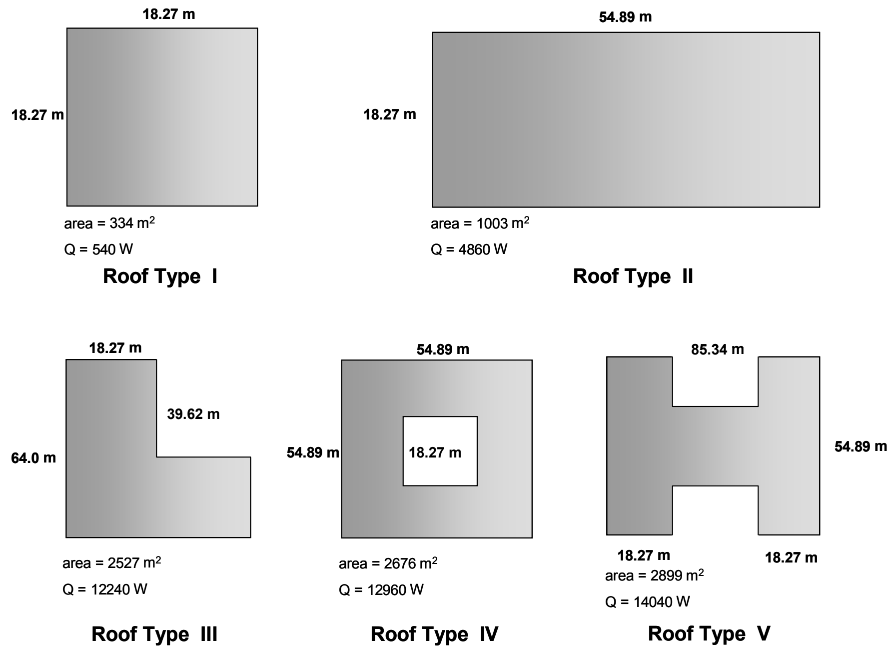


Figure 7. Five diagrams of different roof areas that result in different Q-values.

The following is a line-chart resulted from the above various plan shapes of different roof areas with different heights and constant volume, Figure 8.

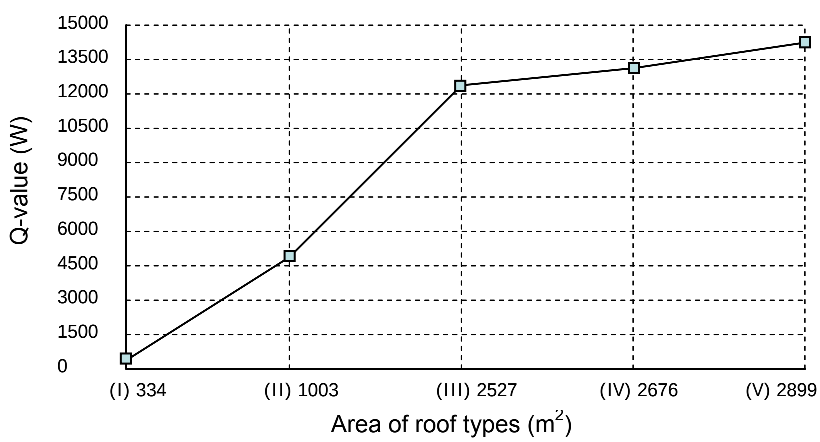


Figure 8. Line chart showing the relationship between the increase in roof areas and Q-values.

WALL LAYER POSITIONING

Change of wall layer positioning without changing wall thickness will result in a different of total heat transmission to penetrate through the wall, and hence, varied thermal efficiency for each wall, Figure 9. Various detailed sections are examined in this stage with typical wall components.

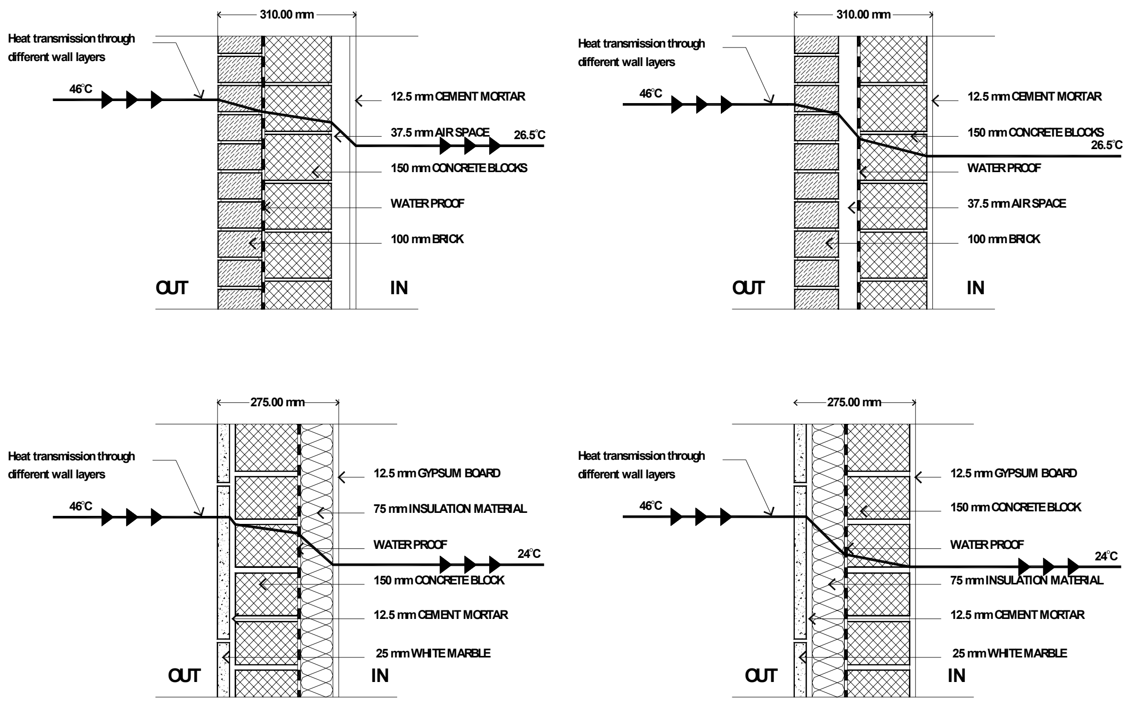


Figure 9. Change of wall layers resulting in an early heat transmission breakdown through the wall.

FINDINGS AND RESULTS

- As roof area increases, total energy received by the roof element Increases.
- Q-value increases or decreases by the effect of plan shapes and roof and wall areas.
- The rate of height increases rapidly with the changes in volume in small buildings, while in large ones, the rate of increase of height with the increase in volume is much less.
- Change of material layers positioning within the same wall mass would result in an early heat break down transmission, and hence, wall thermal performance will be more efficient.

- Wall thickness can be reduced without the reduction of thermal performance. This is initially based on the process of selecting and positioning insulation materials in the wall.
- Positioning the insulation material adjacent to the outer wall surface will contribute to reduced levels of energy consumptions and enhanced thermal efficiency of the wall.

CONCLUSION

- A change of mass components and layers of the wall or roof may increase wall efficiency, and hence, reduce energy consumption.
- The second choice of wall and roof combination in Table 4 is the optimum selection for Makkah during summer, where the fifth combination is the optimum during winter.
- The rate of fabric heat gain varies as the dimensions are changed from the normal values.
- A change of building form affects its overall thermal performance.
- Wall thickness can be reduced without the reduction of thermal performance. This is initially based on the process of selecting and positioning insulation materials in the wall.
- The decision made by a designer to distribute building layout vertically or horizontally will result in an increase or decrease in the total energy consumption of the building.
- In the case of Makkah, it is recommended to decrease the total exposed surface roof area to the sun. In other words, the more the roof area to be exposed to the sun (with the same wall height and constant volume), the larger Q-value to develop, and hence, the higher energy consumption of the total building to be experienced.

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